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(54) **ULTRASOUND GUIDED TISSUE ABLATION**

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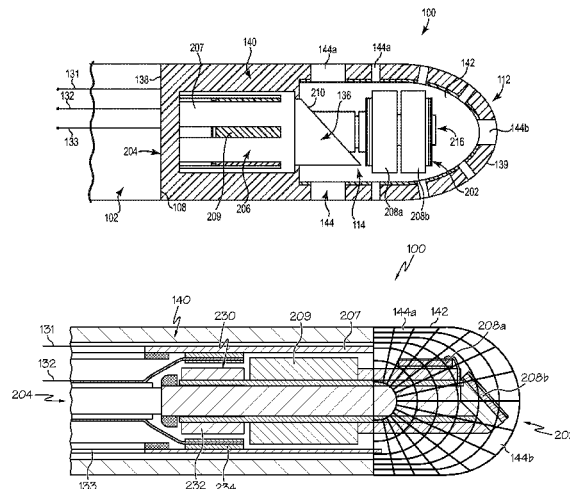
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(57) **ABSTRACT**

An imaging assembly comprises a catheter having a distal end and a proximal end, an ablation tip at the distal end of the catheter, and an imaging device disposed within the ablation tip. The catheter defines a catheter lumen that extends from the proximal end to the distal end. The catheter is configured and arranged for insertion into a body lumen such as a blood vessel or heart chamber. The ablation tip has a wall that defines a lumen in communication with the lumen of the catheter. The imaging device is disposed within the lumen of the ablation tip, and is configured to transmit pulsed acoustic waves for generating images of body tissue at a target ablation site within the body.

20 Claims, 4 Drawing Sheets



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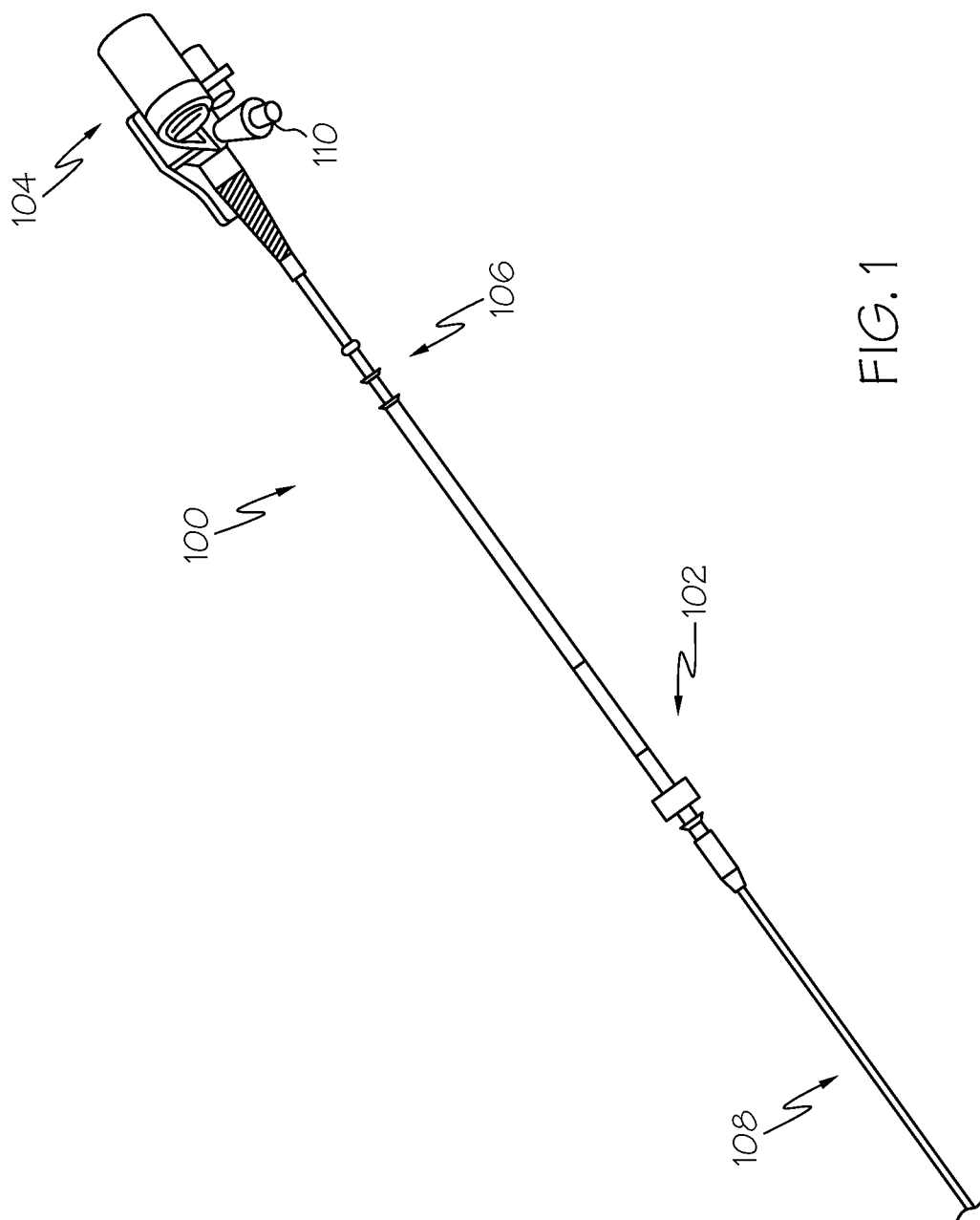
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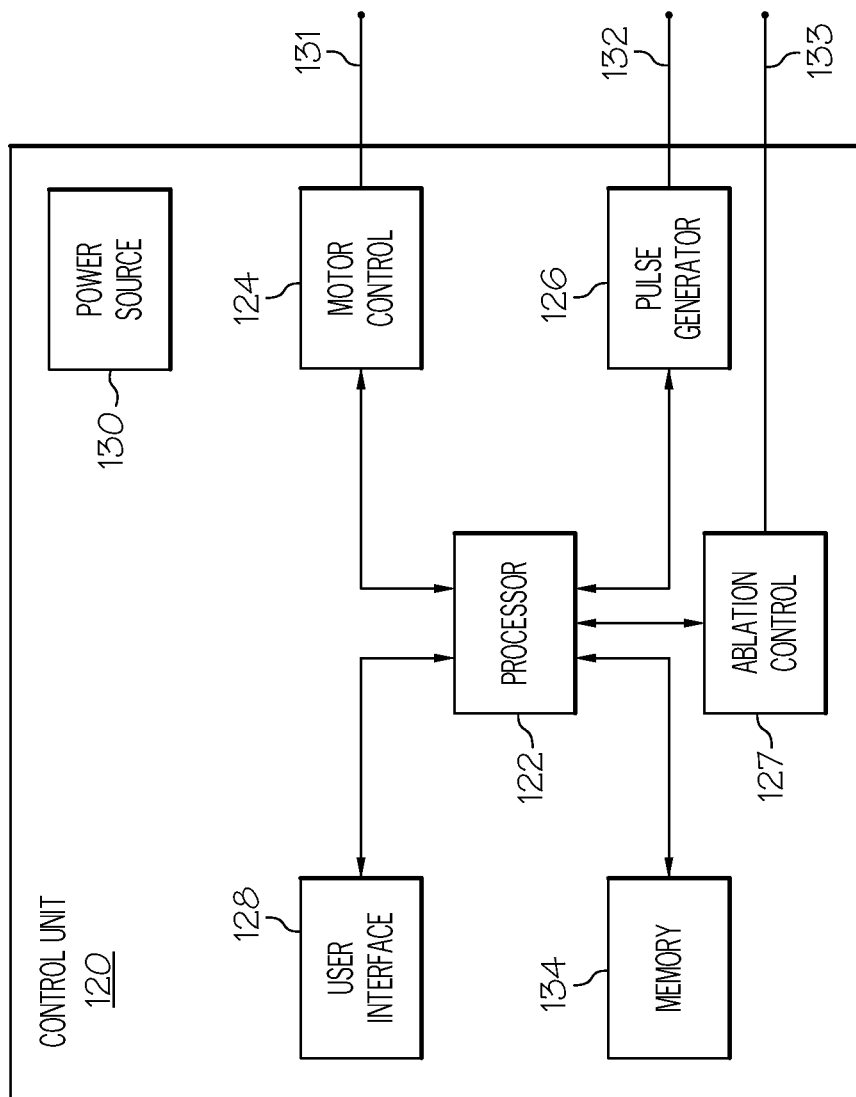
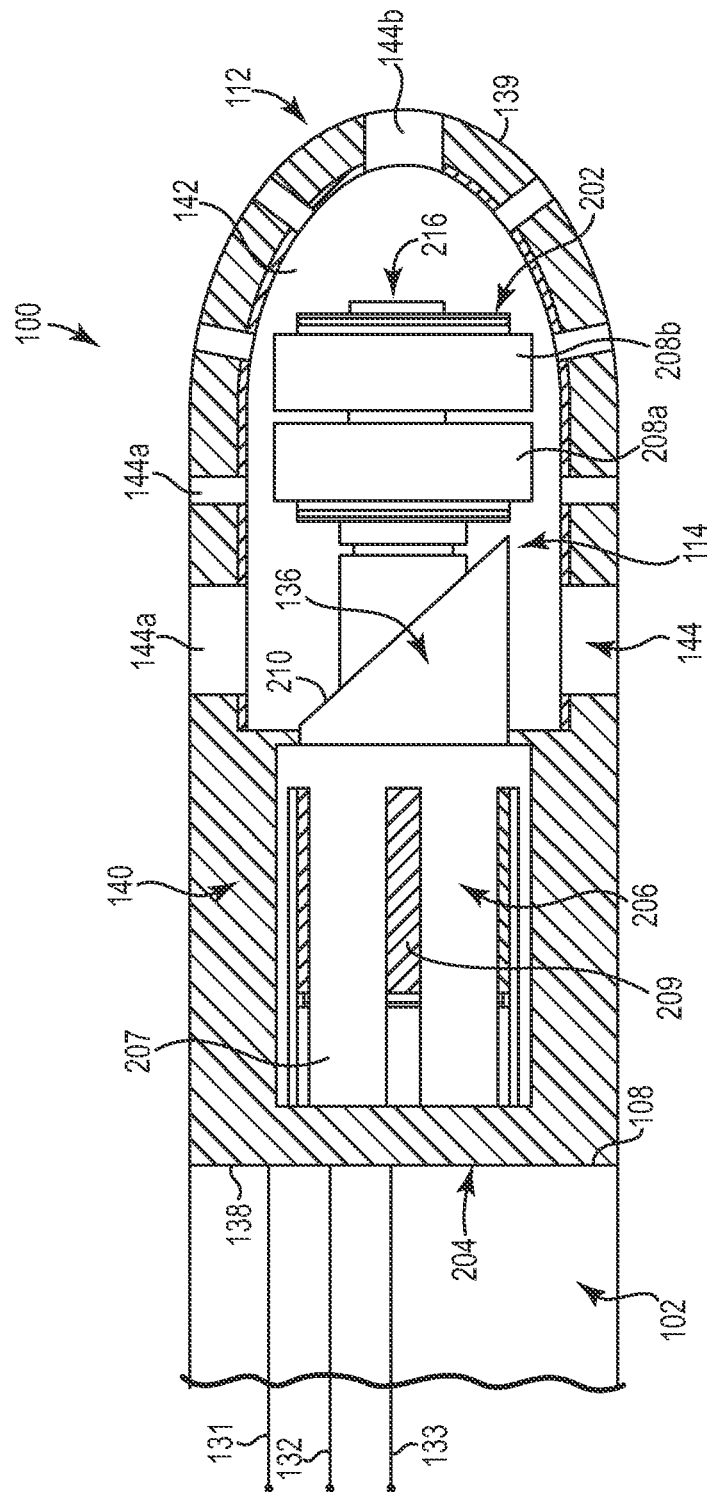


FIG. 2



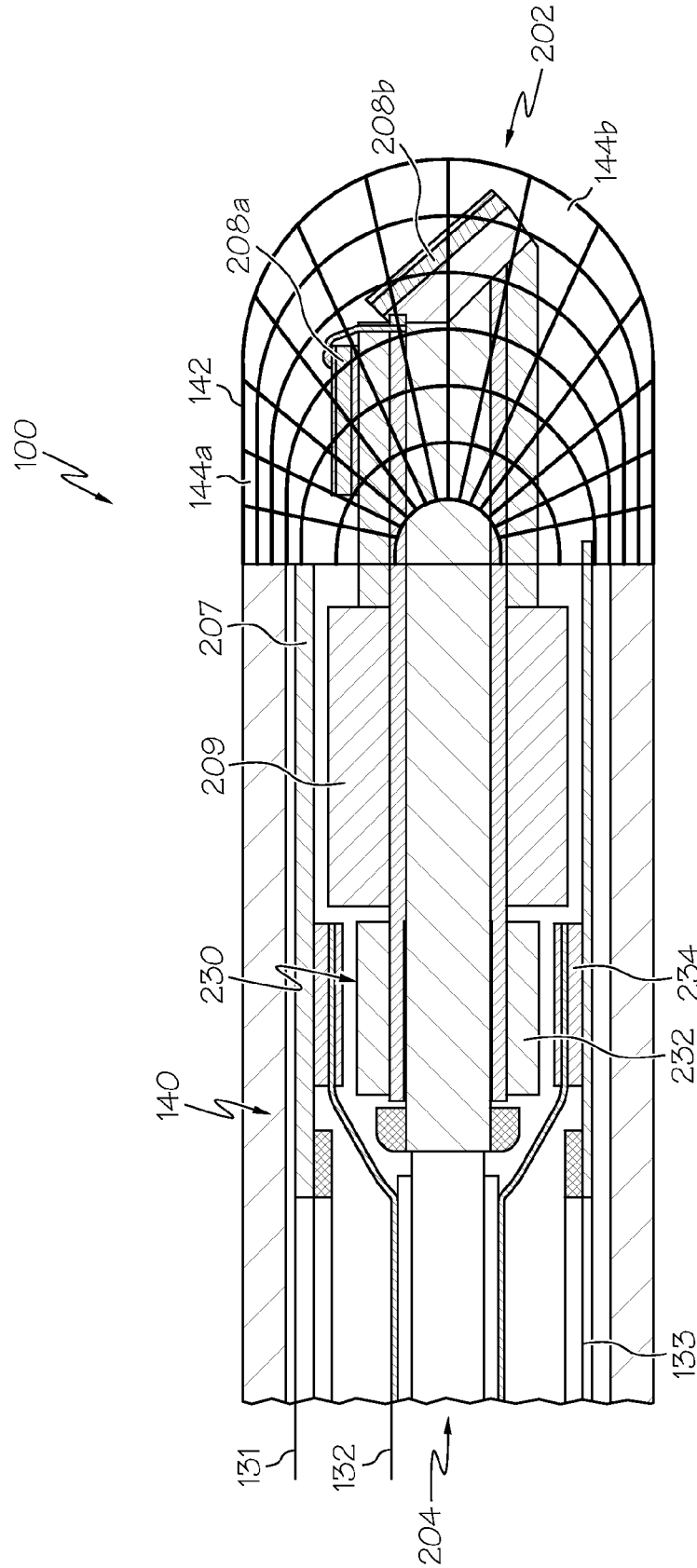


FIG. 4

1

ULTRASOUND GUIDED TISSUE ABLATION**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims priority to both U.S. Provisional Application No. 61/428,798, entitled, "Ultrasound Guided Tissue Ablation," filed on Dec. 30, 2010, and U.S. Provisional Application No. 61/475,390, entitled "Ultrasound Guided Tissue Ablation," filed on Apr. 14, 2011, the contents of which are incorporated herein by reference in their entirety for all purposes.

TECHNICAL FIELD

The present disclosure relates generally to imaging anatomical structures within the body during an ablation procedure. More specifically, the present disclosure relates to ultrasound imaging systems and methods.

BACKGROUND

The present disclosure relates generally to ultrasound imaging systems and methods of making and using such systems. Ultrasound imaging systems, such as intravascular ultrasound ("IVUS") and intracardiac echo ("ICE") imaging systems, provide visual indicia to a practitioner when diagnosing and treating various diseases and disorders. For example, intravascular ultrasound ("IVUS") imaging systems have been used to diagnose blocked blood vessels and to provide information to a practitioner in selecting and placing stents and other devices to restore or increase blood flow to a vessel. IVUS imaging systems have also been used to diagnose plaque build-up in the blood vessels and other intravascular obstructions. Intracardiac echo (ICE) imaging systems are used to monitor one or more heart chambers. Ultrasound imaging systems can be used to visualize images of vascular tissue that are typically visualized using other imaging techniques such as angiography.

An ultrasound imaging system can include a control module, a catheter, and at least one transducer disposed in the catheter. The catheter is configured and arranged for percutaneous insertion into a patient. The catheter can be positioned in a lumen or cavity at or near a region to be imaged, such as a blood vessel wall. Electrical pulses generated by the control module are delivered to the transducer to generate acoustic pulses that are transmitted through the blood vessel wall or other patient tissue. The reflected pulses generated by these acoustic pulses are absorbed by the transducer and transformed into an electrical signal that is converted to an image visible by the practitioner.

Intravascular ultrasound imaging systems (IVUS) typically use short wavelength, high frequency (e.g., 40 MHz) ultrasound to obtain high resolution images of tissues that lie within about 10 mm of the ultrasound transducer. Intracardiac echo (ICE) imaging systems typically use longer wavelength, lower frequency (e.g., 9 MHz) ultrasound to image the walls and structures within a heart chamber that lie within about 300 mm of the ultrasound transducer.

In some procedures where tissue ablation is required, it may be desirable to use a catheter provided with an ablation tip. Examples of ablation catheters including an ablation tip are described, for example, in U.S. Pat. Nos. 5,571,088, 6,352,534, and 7,488,289, each of which is incorporated herein by reference in its entirety for all purposes. In some instances, it may be desirable to have a means for viewing the tissues adjacent to the ablation tip during the ablation procedure.

2

For example, in ablation of tissues of the heart wall to treat arrhythmias, it is important for the ablation to extend through the wall (i.e., transmural ablation), but it is equally important to avoid ablation of sensitive structures, such as the esophagus or the phrenic nerve, that lie just behind the heart wall tissue being ablated. A means of visualizing both the direction and the progression of the ablation is therefore needed.

SUMMARY

The present disclosure describes techniques for ultrasound imaging of tissue within the cardiovascular system. In particular, the present disclosure describes techniques that allow high resolution ultrasound imaging of patient tissue (e.g., of a blood vessel wall or heart chamber) to be performed along with ablation of the tissue using the same catheter. Using various techniques of this disclosure, an ultrasound imaging system may scan the tissue before, during, and after ablation of the tissue in order to obtain a high resolution image of a selected region.

In Example 1, an ultrasound imaging assembly for an ablation system comprises: a catheter having a proximal end and a distal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen; an ablation tip at the distal end of the catheter, the ablation tip having a wall defining a lumen and including a plurality of openings, the lumen of the ablation tip in communication with the lumen of the catheter; and an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising a plurality of ultrasonic transducers and a drive motor.

In Example 2, the imaging assembly of Example 1, wherein each ultrasonic transducer is configured and arranged for transducing applied electrical signals to acoustic signals and for transducing received echo signals to electrical signals.

In Example 3, the imaging assembly of any of Examples 1 or 2, wherein the plurality of ultrasonic transducers comprises a first transducer and a second transducer.

In Example 4, the imaging assembly of Example 3, wherein the first ultrasonic transducer is configured for imaging tissue located distally of the distal end of the ablation tip, and wherein the second ultrasonic transducer is configured for imaging tissue located adjacent to a circumference of the ablation tip.

In Example 5, the imaging assembly of any of Examples 1-3, wherein the motor is coaxially aligned with each of the ultrasonic transducers.

In Example 6, the imaging assembly of any of Examples 1-4, wherein the drive motor includes a stator and a rotor.

In Example 7, the imaging assembly of Example 6, wherein the stator comprises a three-phase winding for receiving three-phase current.

In Example 8, the imaging assembly of any of Examples 1-7, wherein at least one of the ultrasonic transducers is fixed.

In Example 9, the imaging assembly of Example 6, further comprising a reflective surface that is rotatably coupled to the rotor of the motor, and wherein the acoustic signals produced by the at least one fixed ultrasonic transducer are reflected by the reflective surface through the openings.

In Example 10, the imaging assembly of Example 9, wherein the reflective surface is planar.

In Example 11, the imaging assembly of Example 9, wherein the reflective surface is non-planar.

In Example 12, the imaging assembly of Example 6, wherein at least one ultrasonic transducer is rotatably coupled to the rotor.

In Example 13, the imaging assembly of Example 12, wherein the imaging device includes a transformer configured for electrically coupling the at least one ultrasonic transducer to an electrical lead within the lumen of the catheter.

In Example 14, the imaging assembly of Example 13, wherein the transformer is further configured for rotatably coupling the at least one ultrasonic transducer to the rotor.

In Example 15, the imaging assembly of any of Examples 1-14, further comprising a sensing device configured for sensing a location of the ablation tip within the bodily lumen.

In Example 16, the imaging assembly of any of Examples 1-15, wherein the plurality of openings comprises a plurality of side openings and at least one front opening.

In Example 17, the imaging assembly of any of Examples 1-16, further comprising: a user interface; and a control unit electrically coupled to the imaging device.

In Example 18, the imaging assembly of Example 17, wherein the control unit comprises: a pulse generator electrically coupled to the ultrasonic transducers via at least one transducer conductor, the pulse generator configured for generating electric signals that are applied to each ultrasonic transducer during an imaging scan; an ablation control unit electrically coupled to the ablation tip; a motor control unit configured for controlling the motor; and a processor electrically coupled to the ultrasonic transducers via the at least one transducer conductor.

In Example 19, an ultrasound imaging assembly for an ablation system comprises: a catheter having a proximal end and a distal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen; an ablation tip at the distal end of the catheter, the ablation tip having a wall defining a lumen in communication with the lumen of the catheter; and an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising: a first stationary ultrasonic transducer configured for imaging tissue located distally of the distal end of the ablation tip; a second stationary ultrasonic transducer configured for imaging tissue located adjacent to a circumference of the ablation tip; and a drive motor configured for rotating a reflective surface within the lumen of the ablation tip, wherein the reflective surface is configured for reflecting acoustic waves transmitted from and received by the second stationary ultrasonic transducer.

In Example 20, an ultrasound imaging assembly for an ablation system comprises: a catheter having a distal end and a proximal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen; an ablation tip at the distal end of the catheter, the ablation tip having a wall defining a lumen in communication with the lumen of the catheter; and an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising: a first ultrasonic transducer configured for imaging tissue located distally of the distal end of the ablation tip; a stationary ultrasonic transducer configured for imaging tissue located adjacent to a circumference of the ablation tip; and a transformer electrically coupling the first and second ultrasonic transducers to an electrical lead, wherein the transformer is configured for rotating the first and second ultrasonic transducers within the lumen of the ablation tip.

While multiple embodiments are disclosed, still other embodiments of the present invention will become apparent to those skilled in the art from the following detailed descrip-

tion, which shows and describes illustrative embodiments of the invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of an IVUS imaging system in accordance with an illustrative embodiment;

FIG. 2 is a block diagram illustrating an example control unit that may be used in conjunction with the system of FIG. 1;

FIG. 3 is a schematic view of the distal end of a catheter in accordance with an illustrative embodiment; and

FIG. 4 is a schematic view of the distal end of a catheter in accordance with an illustrative embodiment.

While the invention is amenable to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and are described in detail below. The intention, however, is not to limit the invention to the particular embodiments described. On the contrary, the invention is intended to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

The ultrasound imaging system of the present invention includes a catheter provided with an ablation tip and an imaging device capable of producing a circumferential map of ultrasound reflectivity versus depth into body tissue. As discussed further herein, the system in some embodiments further includes a control unit and an imaging device. The device can have a sufficient resolution to enable different types of tissue to be distinguished. By integrating an ultrasound imaging device within an ablation tip of a catheter, visual feedback is provided to a practitioner, allowing the practitioner to visually determine what tissue has been ablated and what tissue is untreated.

FIG. 1 is a schematic view of one example catheter of an intravascular ultrasound imaging system, in accordance with this disclosure. As shown in FIG. 1, a catheter, shown generally as **100** includes elongated member **102** and hub **104**. Elongated member **102** includes proximal end **106** and distal end **108**. Proximal end **106** of elongated member **102** is coupled to hub **104**, and distal end **108** of elongated member **102** is configured and arranged for percutaneous insertion into a patient. In at least some embodiments, the catheter **100** defines one or more flush ports, such as flush port **110**. In one example, flush port **110** is defined in hub **104**. In some examples, hub **104** is configured and arranged to couple to a control unit, as further shown and described with respect to FIG. 2. In some embodiments, elongated member **102** and hub **104** are formed as a unitary body. In other embodiments, elongated member **102** and catheter hub **104** are formed separately and subsequently assembled together. In at least one embodiment, the distal end **108** of the catheter **100** is provided with an ablation tip **112**, as further shown and described with respect to FIG. 3. In at least one embodiment, and as shown in FIG. 3, an imaging device **114** is disposed within at least a portion of the ablation tip **112**.

FIG. 2 is a block diagram illustrating an embodiment control unit **120** that may be used to implement various techniques of this disclosure. In the embodiment depicted in FIG. 2, control unit **120** includes a processor **122** that controls a motor control unit **124**, a pulse generator **126**, an ablation control unit **127**, and a user interface **128**. In some embodi-

ments, electric signals, e.g., pulses, transmitted from one or more transducers of the imaging device **114** are received as inputs by processor **122** for processing. In one embodiment, the processed electric signals from transducer(s) located within the catheter **100** are displayed as one or more images on a display of the user interface **128**. In some embodiments, radio frequency current determined by the ablation control unit **127** is transmitted by the control unit **120** to the ablation tip **112**.

Processor **122** is configured to control the functionality of one or more other components of the control unit **120**. In one embodiment, processor **122** is used to control at least one of the frequency or duration of the electrical signals transmitted from pulse generator **126**, the radio frequency signals transmitted from the ablation control unit **127**, the current provided to the imaging device **114** by the motor control unit **124**, or one or more properties of one or more images formed on a display. Processor **122** can also be used to control the ablation tip **112**.

Processor **122** can include any one or more of a controller, a microprocessor, an application specific integrated circuit (ASIC), a digital signal processor (DSP), a field-programmable gate array (FPGA), or equivalent discrete or integrated logic circuitry. The functions attributed to processor **122** can be embodied as hardware, software, firmware, as well as combinations of hardware, software, and firmware.

The control unit **120** further includes power source **130**, which delivers operating power to the components of control unit **120**. In one embodiment, power source **130** includes a battery and power generation circuitry to generate the operating power. In addition, control unit **120** includes a motor control unit **124**, which is configured to supply a current output to a motor (e.g., motor **206** in FIG. 3) in the imaging device **114** of catheter **100** via one or more leads **131**. In some embodiments, a current calculation module may be provided to determine the appropriate current to supply to the motor, which, in some instances, generates a magnetic field that directs a reflective surface or transducer of the imaging device to any selected angle relative to fixed stator windings of the motor. Further description an example current calculation module and techniques for controllably manipulating the imaging device depending on the supplied current are further described, for example, in co-pending Application No. 61/428,567, filed on Dec. 30, 2010, the contents of which are incorporated herein by reference in their entirety for all purposes.

The pulse generator **126** generates electrical signals (e.g., pulses) that are applied via one or more leads **132**, such as a coaxial cable, to one or more ultrasound transducers (e.g., transducer **208** of FIG. 3) of the imaging device **114**. The ablation control unit **127** supplies a radio frequency (RF) current output to the ablation tip **112** of catheter **100** via one or more leads **133**.

User interface **128** includes a display such as a touch screen display or other display, and in some embodiments, includes a keyboard and a peripheral pointing device such as a mouse, that allows the operator to provide input to the control unit **120**.

In some embodiments, the control unit **120** further includes a memory **134**. Memory **134** may include computer-readable instructions that, when executed by the processor **122**, cause the processor **122** to perform various functions ascribed to the control unit **120**, processor **122**, motor control unit **124**, pulse generator **126**, ablation control unit **127**, and user interface **128**. The computer-readable instructions may be encoded within the memory **134**. Memory **134** may comprise computer-readable storage media such as a random access

memory (RAM), read-only memory (ROM), non-volatile RAM (NVRAM), electrically-erasable programmable ROM (EEPROM), flash memory, or any other volatile, non-volatile, magnetic, optical, or electrical media. In some embodiments, a processor (e.g., processor **122**) determines, based on user input defining a range of angles through which a scan will be performed, one or more current values to be applied to one or more leads of a stator of a micro-motor located in the imaging device **114** of catheter **100**, as described further herein.

FIG. 3 is a schematic view of an embodiment of the imaging device **114** disposed within an ablation tip **112**. Ablation tip **112** has a proximal end **138**, a distal end **139**, and a wall **140** therebetween that defines a lumen **142**. In one embodiment, the proximal end **138** abuts the distal end **108** of the elongated member **102**. In some embodiments, elongated member **102** and ablation tip **112** are formed as a unitary body. In other embodiments, elongated member **102** and catheter hub **104** are formed separately and subsequently assembled together. In some embodiments, such as the embodiment shown in FIG. 3, the ablation tip **112** has an arcuate surface at a distal end of the ablation tip **112**.

In some embodiments, the ablation tip **112** has a plurality of openings **144** in the wall **140** of the ablation tip **112**. At least some of the openings **144** extend entirely through a thickness of the wall **140**. In at least some embodiments, an acoustically transparent membrane can be disposed across the least one opening **144**, which allows the transducer to transmit or receive signals while preventing fluid transmission there-through. In at least one embodiment, the ablation tip **112** has a plurality of side openings **144a** that are circumferentially disposed about the ablation tip **112** and at least one front opening **144b**. In some embodiments, the side openings **144a** can be used for imaging, irrigation, or both. In some embodiments, the front opening **144b** can be used for imaging, irrigation or both. In some embodiments, each opening **144** has the same width. In other embodiments, as shown in FIG. 3, some of the openings have greater widths than other openings. In some embodiments, a fluid transferred to the lumen **142** is flushed through at least one of the openings **144** to cool the ablation tip **112**. In at least one embodiment, the fluid is saline. In at least one embodiment, where cooling is not required, the ablation tip **112** can be entirely sealed with an acoustically transparent membrane so that the catheter is fluidtight. In an alternative embodiment where cooling is required, cooling fluid may be circulated through lumen **142** without exiting the ablation tip **112**.

The imaging device, shown generally at **114**, has a proximal end **204** and a distal end **202**. At least a portion of the imaging device **114** is disposed within the lumen **142** of the ablation tip **112**. In some embodiments, the proximal end **204** of the imaging device **114** is disposed within the lumen **142** of the ablation tip **112**. In some embodiments, the entirety of the imaging device **114** is disposed within the ablation tip **112** between the proximal end **138** and the distal end **139** of the tip **112**. Imaging device **114** includes motor **206** (e.g., stepper motor, DC brushless motor, or other suitable motor) and one or more transducers **208** configured and arranged for transducing applied electrical signals received from pulse generator **126** (FIG. 2) via lead(s) **132** to acoustic signals and also for transducing received echo signals to electrical signals. In some embodiments, the transducer **208** is a fixed transducer capable of transmitting electrical signals to the tissue surrounding the ablation tip **112** and receiving echo signals from said tissue. In at least one embodiment, these signals are transmitted and received through the openings **144** of the ablation tip **112**.

This arrangement is capable of generating a high resolution image of tissue (viewable by the practitioner via the visual displays associated with the control unit **120**) adjacent to the ablation tip **112** that can guide the ablation procedure and allow the practitioner to assess the extent of ablation. In some embodiments, when multiple ablations are performed (e.g., to form a line of conduction block), the acquired ultrasound images can be combined to insure that no gaps exist in the line of conduction block. By integrating the imaging device **114** into the tip **112** of the ablation catheter **100**, there is no relative motion between the tip **112** and the imaging transducer, which may be the case if a second catheter were used for the imaging device **114**.

In at least one embodiment, the motor **206** is a micro-motor. The motor **206** includes a rotatable magnet **209** and a stationary stator **207**. In some embodiments, motor **206** is positioned proximal to transducer(s) **208**, as shown, for example, in FIG. 3. In other embodiments, the motor **206** is positioned distal to transducer(s) **208**. As seen in FIG. 3, the motor **206** is coaxially aligned with transducer(s) **208**. However, in other examples, motor **206** does not share a common axis with transducer(s) **208**. The control unit **120** is electrically connected to motor **206** via leads **131**, to the transducer **208** via leads **132**, and to the ablation tip **112** via leads **133**. In some embodiments, the leads **131**, **132**, **133** comprise shielded electrical cables such as coaxial cables, twisted pair cables, and the like that extend along at least a portion of the longitudinal length of the catheter **100**.

In at least one embodiment, the magnet **209** for the motor **206** is formed from a magnetic material suitable for retrievable medical devices including, but not limited to, neodymium-iron-boron and other similar materials. In some embodiments, the magnet has a magnetization *M* of more than about 1.4 T. In some embodiments, the magnet has a magnetization *M* of more than about 1.5 T. In some embodiments, the magnet has a magnetization *M* of more than about 1.6 T. In some embodiments, the magnet has a magnetization vector that is perpendicular to the longitudinal axis of the magnet.

In some embodiments, the stator **207** includes at least two perpendicularly-oriented magnetic field windings, which provide a rotating magnetic field to produce torque that causes rotation of the rotor. In some embodiments, the stator **207** comprises three perpendicularly-oriented magnetic field windings. In some embodiments, the diameter of the wire used to form the windings is less than about 0.004 inches (0.010 cm). In some embodiments, the diameter of the wire is less than about 0.003 inches (0.008 cm). In some embodiments, the diameter of the wire is less than about 0.002 inches (0.005 cm). In some embodiments, the stator **207** is formed from a slotted metal tube. In some embodiments the wall thickness of the slotted metal tube is less than 0.003 inches (0.008 cm). In at least some embodiments the slotted metal tube stator **207** comprises three metal strips that carry the three phases of a three phase current motor to create a rotating magnetic field at the location of the magnet **209**. The stator **207** is provided with current from the control unit **120** via one or more leads **131** that is applied to the magnetic field windings.

In some embodiments, imaging device **114** further includes a reflective surface **210** such as a mirror. The reflective surface **210** can be a reflective surface of a magnet **209** of motor **206** or, in some embodiments, a reflective surface either disposed on or coupled to the magnet **209**. As shown in FIG. 3, in some embodiments, the reflective surface **210** is tilted at an angle that is not parallel with either a longitudinal axis of the catheter **100** or a diameter of the catheter **100**.

In some embodiments, the reflective surface **210** is tilted at an angle so that acoustic signals output from transducer(s) **208** (e.g., pulses of ultrasound energy) are reflected in a direction that is not parallel to longitudinal axis of the imaging device **114**. In at least one embodiment, the reflective surface **210** is tilted at an angle so that the acoustic signals output from transducers **208** are reflected toward patient tissue in a direction that is approximately perpendicular to the longitudinal axis of the imaging device **114**.

The reflective surface **210** is tilted at an angle so that at least some of the echo signals received from patient tissue, in response to the acoustic signals output from transducer(s) **208**, are reflected back to transducers **208**. The echo signals are transduced into electric signals and transmitted to the processor **122** for generating an image. In some embodiments, the reflective surface **210** is tilted at an angle so that at least some of the echo signals from patient tissue are reflected to a direction that is parallel to longitudinal axis of imaging device **114**. In some embodiments, for example, the reflective surface **210** is tilted at an angle in the range of between about 30 degrees and 60 degrees relative to the longitudinal axis. In one embodiment, the reflective surface **210** is tilted at an angle of about 45 degrees relative to the longitudinal axis.

The at least one transducer **208** transmits and receives acoustic pulses generated from electrical pulses received from control unit **120**. The at least one transducer **208** is formed from one or more known materials capable of transducing applied electrical pulses to pressure distortions at the surface of the transducers, and vice versa. Examples of such materials include, but are not limited to, piezoelectric ceramic materials, piezocomposite materials, piezoelectric plastics, barium titanates, lead zirconate titanates, lead metaniobates, and polyvinylidene fluorides. The pressure distortions at the surface of the transducer **208** form acoustic pulses of a frequency based on the resonant frequency of the transducer **208**. The resonant frequency of the transducer **208** can be affected by the size, shape, and material used to form the transducer **208**.

In one embodiment, each transducer **208** includes a layer of piezoelectric material sandwiched between electrically conductive coatings such as, for example, a conductive acoustic lens and a conductive backing material formed from an acoustically absorbent material. In some embodiments, during operation, the piezoelectric layer is electrically excited by applying a voltage pulse between the conductive coatings. In some embodiments, the back surface of the piezoelectric material is further coated with a material that absorbs ultrasound energy. In some embodiments, the front surface of the piezoelectric material is further coated with an impedance matching layer that has acoustic impedance midway between the acoustic impedance of the piezoelectric material and the acoustic impedance of the surrounding fluid. Ultrasound energy is projected only from the front surface of the composite transducer into the lumen **142** and through the openings **144**.

The transducer **208** can be formed in any shape suitable for positioning within the catheter **100** and for propagating acoustic pulses of a desired frequency in one or more selected directions. In some embodiments, an array of transducers **208** can be used. In some embodiments, the transducer **208** can be in the form of discs, blocks, rectangles, ovals, and other shapes. The transducer can be formed in the desired shape by any process including, for example, dicing, dice and fill, machining, microfabrication, and similar processes.

In some embodiments, and as shown in FIG. 3, the transducer **208** can be used to form a radial cross-sectional image of a surrounding space by rotating a reflective surface **210**

attached to the rotor that reflects the signals from a stationary transducer **208** to the blood vessel wall or tissue and vice versa. In another embodiment, shown in FIG. **4**, the transducer **208** can be used to form a radial cross-sectional image of a surrounding space by rotating the transducer **208**. Thus, when the catheter **100** is inserted into a blood vessel of a patient, for example, the signals received from the transducer **208** by the control unit **120** are processed and form a plurality of images that collectively form a radial cross-sectional image of a portion of the region surrounding the one or more transducers **208**, such as the walls of a blood vessel of interest and the tissue surrounding the blood vessel. In at least some embodiments, the radial cross-sectional image can be displayed on one or more displays. In other embodiments, tissue adjacent ablation tip **112** is imaged by sweeping the reflective surface **210** back and forth through an arc of angles that subtends the tissue, using appropriate currents applied to motor **206**.

The quality of an image produced from the at least one transducer **208** can be affected by certain factors, including, but not limited to, bandwidth, transducer focus, beam pattern, as well as the frequency of the acoustic pulse. The frequency of the acoustic pulse from the transducer **208** can also affect the penetration depth of the acoustic pulse. In general, as the frequency of an acoustic pulse is lowered, the depth of the penetration of the acoustic pulse within patient tissue increases and the image resolution decreases. In at least some embodiments, the imaging device operates within a frequency range of 5 MHz to 60 MHz.

FIG. **3** shows a cross-section of an embodiment where the rotor **136** is fixedly attached to a rotatable reflective surface **210** that reflects the signals from a stationary transducer **208** to the blood vessel wall or tissue and vice versa. As the rotatable reflective surface **210** rotates with the rotor **136**, the emitted acoustic pulses from the stationary transducer **208** are reflected outward to the tissue. When an emitted acoustic pulse with sufficient energy encounters one or more boundaries, such as a tissue boundary, a portion of the emitted acoustic pulse is reflected back to the reflective surface **210**, and then reflected back to the transducer **208** as an echo pulse. Each echo pulse that reaches the transducer **208** with sufficient energy to be detected is transduced to an electrical signal by the transducer **208**. The electrical signal is then transmitted to the control unit **120** where the processor **122** processes the electrical-signal characteristics to form a displayable image of the imaged region based, at least in part, on a collection of information from each of the acoustic pulses transmitted and the echo pulses received.

In some embodiments, the rotating reflective surface **210** is positioned proximal to the one or more fixed transducers **208**. In some embodiments, the rotating reflective surface **210** is positioned distal to the one or more fixed transducers **208**. In some embodiments, the rotating reflective surface **210** is disposed distally on the rotor **136**, with the fixed transducer **208** disposed either proximal to the rotor **136**, inside an aperture of the rotor **136**, or distal to the rotor **136**. In at least some embodiments, the rotating reflective surface **210** is fixedly coupled to the rotor **136** such that the reflective surface **210** rotates with the rotor **136**.

In some embodiments, the reflective surface **210** is planar. In some embodiments, the reflective surface **210** is non-planar. In at least one embodiment, the reflective surface **210** is concave. In at least one embodiment, the reflective surface **210** is convex. In at least some embodiments, the shape of the reflective surface **210** is adjustable in order to allow for variable focus or depth of field for imaging tissues. In at least some embodiments, the reflective surface **210** is a coated

membrane stretched over a space that contains air or other compressible substance. In some embodiments, when the pressure of the region between the one or more transducers **208** and the reflective surface **210** increases, the reflective surface **210** may deflect to produce a concave surface.

FIG. **4** is a schematic view of an embodiment of the imaging device **114** disposed within an ablation tip **112**. As shown in FIG. **4**, the imaging device **114** further comprises at least one transformer **230** electrically coupled to the transducer **208**. At least in embodiments where the transducer **208** is rotatable, the transformer **230** is used to electrically couple the stationary components of the ultrasound imaging system (e.g., the control unit **120**) with the rotating transducer **208**. In some embodiments, the transformer **230** comprises a rotating component **232**, such as a rotating solenoid, and a stationary component **234**, such as a stationary solenoid. The rotating component **232** is spaced apart from the stationary component **234**. In some embodiments, the transformer **230** uses inductive coupling between the rotating component **232** and the stationary component **234**. Current from the control unit **120** can be induced in the rotating component **232** from the stationary component **234**. The induced current can then be transmitted to the one or more transducers **208**, where the current (i.e., the electrical pulses received from the control unit **120**) is transduced into an acoustic signal and emitted as one or more acoustic pulses. Echo pulses received by the one or more transducers are then transduced into electrical signals and transmitted to the rotating component **232**. A voltage may be induced in the stationary component **234** by the electrical signal in the rotating component **232**. In some embodiments, the voltage can be applied as an input to the control unit **120**.

In some embodiments, the transformer **230** is positioned at a proximal end of the imaging device **114**. In some embodiments, one or more leads **132** electrically couple the transformer **230** to the control unit **120**. In some embodiments, the stationary component **234** of the transformer **230** is electrically coupled to the control unit **120** via the leads **132**. In some embodiments, the leads **132** extend along at least a portion of the longitudinal length of the catheter **100**. In some embodiments, the leads **132** are shielded electrical cables, such as a coaxial cable, a twisted pair cable, or other similar cables.

In some embodiments, the transformer **230** is positioned at a distal end of the imaging device. In at least one embodiment, one or more leads (not shown) electrically couple the transducer **208** to the rotating component **232** of transformer **230**. In other embodiments, the transformer **230** is positioned proximal to the transducer **208**. In some embodiments, the transformer **230** is positioned distal to the transducer **208**.

In some embodiments, the rotating component **232** and the stationary component **234** of the transformer **230** are proximate a ferrite material. In at least one embodiment, the rotating component **232** and the stationary component **234** are formed from a wire. In some embodiments, the diameter of the wire is less than about 0.004 inches (0.010 cm). In some embodiments, the diameter of the wire is less than about 0.003 inches (0.008 cm). In some embodiments, the diameter of the wire is less than about 0.002 inches (0.005 cm).

In some embodiments, the motor **206** provides enough torque to rotate the one or more transducers **208** at a frequency of at least 15 Hz. In some embodiments, the motor **206** provides enough torque to rotate the one or more transducers **208** at a frequency of at least 20 Hz. In some embodiments, the motor **206** provides enough torque to rotate the one or more transducers **208** at a frequency of at least 25 Hz. In some embodiments, the motor **206** provides enough torque to rotate the one or more transducers **208** at a frequency of at least 30 Hz. In some embodiments, the motor **206** provides

enough torque to rotate the one or more transducers **208** at a frequency of at least 35 Hz. In some embodiments, the motor **206** provides enough torque to rotate the one or more transducers **208** at a frequency of at least 40 Hz. In some embodiments, the transducer operates at a frequency of about 10 MHz with an image penetration depth of up to 50 mm into tissue. In some embodiments, the transducer operates at a frequency of about 40 MHz with an image penetration depth of up to 8 mm, typically between 5-8 mm, into tissue. The image penetration depth is dependent upon both the frequency and the type of tissue being viewed.

In some embodiments, such as those shown in FIGS. 3 and 4, the imaging device **114** has a side looking transducer **208a** and a forward looking transducer **208b**. The side looking transducer **208a** is capable of producing a view of tissue adjacent to the ablation tip in a radial direction. The forward looking transducer **208b** is capable of producing a view of tissue adjacent to the distal end of the ablation tip in an axial direction. In some embodiments, where the transducers are rotated such as the embodiment shown in FIG. 4, the forward looking transducer **208b** rotates with the side looking transducer **208a**. In some embodiments, the side looking transducer **208a** and the forward looking transducer **208b** are separately controllable by the control unit **120**. For example, in one embodiment the control unit **120** sends and receives independent electrical signals to the side looking transducer **208a** and the forward looking transducer **208b** through separate electrical leads. In some embodiments, and as shown in FIG. 4, the forward looking transducer **208b** is tilted at an angle that is not parallel with either a longitudinal axis of the catheter **10** or a diameter of the catheter **100**.

In some embodiments, and as shown in FIG. 4, the wall **140** of the ablation tip **112** comprises a mesh material. The mesh material can be made from a metal, polymer, or a combination of both. In some embodiments, the wall **144** of the ablation tip **112** comprises first and second ablation electrodes that are separated by an opening through which transducers **208a**, **208b** are capable of transmitting and receiving acoustic signals. RF current can be passed between the two electrodes, known as "bi-polar ablation." Additional electrodes may optionally be provided on the catheter **100**. In some embodiments, a distal portion of the ablation tip **112** is electrically insulated. In some embodiments, the inside surfaces of the ablation tip **112** are covered with an ultrasound absorbing material to prevent reflections from the inside surfaces of the ablation tip **112** back to the transducers **208a**, **208b**.

In some embodiments, the RF frequencies are selectively filtered by the control unit **120** from the signals received from the transducer by the control unit **120**. In some embodiments, low pass filtering may be adequate since the RF frequency is typically near 500 kHz while the ultrasound imaging may be near 40 MHz. In some embodiments, the ablation and imaging of the tissue can be done sequentially, for example by ablating for a first period of time, imaging for a second period of time, and repeating until the ablation is completed. In some embodiments, the first period of time and the second period of time are less than 1 second.

In some embodiments, the imaging device **114** defines a guidewire lumen **216**, which extends at least from the proximal end **202** of imaging device **114** to the distal end **204** of imaging device **114**. As shown in FIG. 3, the motor **206**, transducer(s) **208**, and reflective surface **210** are disposed about guidewire lumen **216**, which allows the guidewire lumen **216** to extend completely through the imaging device. In some embodiments such as the embodiment shown in FIG. 3, the imaging device can have a guidewire lumen **216** that extends through the rotor **136** and which is configured to

receive a guidewire. In some embodiments, the catheter **100** is steered by actuation wires without the use of a guidewire. In such embodiments, the diameter of the guidewire lumen **216** may be minimized to a tube that contains leads **132** of the transducer, which allows for a transducer having a greater area and a reflective surface with a greater area.

In some embodiments, the imaging device **114** can be disposed within the lumen of the catheter **100** and a second catheter equipped with an ablation tip can be disposed within the lumen of catheter **100** and through a guidewire lumen within an imaging device that does not include an ablation tip. In some embodiments, the imaging system may be used with an optical coherence tomography (OCT) system such as that described, for example, in co-pending Application No. 61/428,563, filed on Dec. 30, 2010, the contents of which are incorporated herein by reference in their entirety for all purposes. Additional details describing IVUS imaging systems may be found, for example, U.S. Pat. Nos. 6,945,938 and 7,306,561; U.S. Patent Application Publication Nos. 2006/0100522, 2006/0253028, 2007/0016054, 2007/0003811, 2010/0249599, 2010/0249603, and 2010/0249604; and U.S. application Ser. Nos. 12/565,632 and 12/566,390, each of which is incorporated herein by reference in its entirety for all purposes.

In any of the embodiments, the imaging device **114** can also have a sensing device for sensing the location or orientation of the imaging device **114**. In some embodiments, a magnetic sensing device is provided that measures an amplitude or orientation of the rotating magnetic field vector produced by the rotating magnet of the motor. In some embodiments, data from the magnetic sensing device may be input to a drive circuit to provide controlled rotation of the imaging device **114** (e.g., through a feedback loop). In any of the embodiments, a sensing device can be provided for sensing the location or orientation of the ablation tip **112**. The data provided by these sensing devices can be used to make an anatomical map of the vessel or organ or portion thereof, such as the heart chamber. The data provided by these sensing devices can also be used for electro-anatomical mapping. The data can also be used to plot the current position of the ablation tip **112** and can be combined with data from a local electrocardiogram. In some embodiments, the sensing device is located outside of the patient.

The above disclosure is not limited to vascular applications, and can be used in other bodily lumens that are accessible by catheters. In one example of a vascular application, the catheter **100** could be used to ablate nerves and ganglia adjacent the renal artery to control hypertension. In such applications, the cooling required for the tip may be adjusted by the control unit **120** based upon visual indicia provided by the imaging device **114**. For example, the cooling may be adjusted to a depth at which the nerves reside, without ablating adjacent muscle tissue or endothelium that may be immediately adjacent to the ablation tip.

Various modifications and additions can be made to the exemplary embodiments discussed without departing from the scope of the present invention. For example, while the embodiments described above refer to particular features, the scope of this invention also includes embodiments having different combinations of features and embodiments that do not include all of the described features. Accordingly, the scope of the present invention is intended to embrace all such alternatives, modifications, and variations as fall within the scope of the claims, together with all equivalents thereof.

What is claimed is:

1. An ultrasound imaging assembly for an ablation system, the imaging assembly comprising:

13

- a catheter having a proximal end and a distal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen;
- an ablation tip at the distal end of the catheter, the ablation tip having a wall that defines a lumen, the wall including a plurality of openings, the lumen of the ablation tip in communication with the lumen of the catheter, the wall formed by metal and configured to deliver ablation energy to tissue; and
- an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising a plurality of ultrasonic transducers disposed within the lumen of the ablation tip and positioned to direct acoustic signals through the plurality of openings, respectively, the imaging device further comprising a drive motor within the lumen of the ablation tip.
2. The imaging assembly of claim 1, wherein each ultrasonic transducer is configured and arranged for transducing applied electrical signals to the acoustic signals and for transducing received echo signals to electrical signals.
3. The imaging assembly of claim 1, wherein the drive motor is configured to receive electrical current that drives the drive motor to rotate.
4. The imaging assembly of claim 1, wherein the plurality of ultrasonic transducers comprises a first transducer and a second transducer, the first ultrasonic transducer is configured for imaging tissue located distally of the distal end of the ablation tip, and wherein the second ultrasonic transducer is configured for imaging tissue located adjacent to a circumference of the ablation tip.
5. The imaging assembly of claim 1, wherein the motor is coaxially aligned with each of the ultrasonic transducers.
6. The imaging assembly of claim 1, wherein the drive motor includes a stator and a rotor.
7. The imaging assembly of claim 6, wherein the stator comprises a three-phase winding for receiving three-phase current.
8. The imaging assembly of claim 6, wherein at least one of the ultrasonic transducers is fixed.
9. The imaging assembly of claim 8, further comprising a reflective surface that is rotatably coupled to the rotor of the motor, and wherein the acoustic signals produced by the at least one fixed ultrasonic transducer are reflected by the reflective surface through the openings.
10. The imaging assembly of claim 9, wherein the reflective surface is planar.
11. The imaging assembly of claim 9, wherein the reflective surface is non-planar.
12. The imaging assembly of claim 6, wherein at least one ultrasonic transducer is rotatably coupled to the rotor.
13. The imaging assembly of claim 12, wherein the imaging device includes a transformer configured for electrically coupling the at least one ultrasonic transducer to an electrical lead within the lumen of the catheter.
14. The imaging assembly of claim 13, wherein the transformer is further configured for rotatably coupling the at least one ultrasonic transducer to the rotor.
15. The imaging assembly of claim 1, further comprising a sensing device configured for sensing a location of the ablation tip within the bodily lumen.
16. The imaging assembly of claim 1, wherein the plurality of openings comprises a plurality of side openings and at least one front opening.
17. The imaging assembly of claim 1, further comprising:
a user interface; and
a control unit electrically coupled to the imaging device.

14

18. The imaging assembly of claim 17, wherein the control unit comprises:
a pulse generator electrically coupled to the ultrasonic transducers via at least one transducer conductor, the pulse generator configured for generating electric signals that are applied to each ultrasonic transducer during an imaging scan;
an ablation control unit electrically coupled to the ablation tip;
a motor control unit configured for controlling the motor; and
a processor electrically coupled to the ultrasonic transducers via the at least one transducer conductor.
19. An ultrasound imaging assembly for an ablation system, the imaging assembly comprising:
a catheter having a proximal end and a distal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen;
an ablation tip at the distal end of the catheter, the ablation tip having a wall defining a lumen in communication with the lumen of the catheter; and
an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising:
a first stationary ultrasonic transducer located within the lumen of the ablation tip, the first stationary ultrasonic transducer configured to generate acoustic pulses and orientated to project the acoustic pulses in a first direction distally of the distal end of the ablation tip for imaging tissue located distally of the distal end of the ablation tip;
a second stationary ultrasonic transducer located within the lumen of the ablation tip, the second stationary ultrasonic transducer coaxially aligned with the first stationary ultrasonic transducer, the second stationary ultrasonic transducer configured to generate acoustic pulses and orientated to project the acoustic pulses in a second direction that is opposite the first direction; and
a drive motor configured for rotating a reflective surface within the lumen of the ablation tip, wherein the reflective surface is configured for reflecting the acoustic pulses generated by the second stationary ultrasonic transducer in a lateral direction with respect to the ablation tip for imaging tissue located adjacent to a circumference of the ablation tip.
20. An ultrasound imaging assembly for an ablation system, the imaging assembly comprising:
a catheter having a distal end and a proximal end, the catheter defining a catheter lumen extending from the proximal end to the distal end, the catheter configured and arranged for insertion into a bodily lumen;
an ablation tip at the distal end of the catheter, the ablation tip having a wall defining a lumen in communication with the lumen of the catheter; and
an imaging device disposed at least in part within the lumen of the ablation tip, the imaging device comprising:
a first ultrasonic transducer configured for imaging tissue located distally of the distal end of the ablation tip;
a second ultrasonic transducer configured for imaging tissue located adjacent to a circumference of the ablation tip; and
a transformer comprising a stator and a rotor, the stator and the rotor inductively coupled to one another, the transformer electrically coupling the first and second ultrasonic transducers to an electrical lead via the inductive coupling between the stator and the rotor,

15

wherein the transformer is configured for rotating the first and second ultrasonic transducers within the lumen of the ablation tip.

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16